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Russell James Sojourner

A thesis submitted to the Graduate Faculty of
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Approved By:

Donald H. Mershon Richard G. Pearson

Jonathan F. Antin
Chairman of Advisory Committee

Abstract

SOJOURNER, RUSSELL J. The Head-Up Display in the Automobile Environment (Under the direction of Dr. Jonathan F. Antin). The head-up display (HUD) enables the user to view critical instrumentation without redirecting his or her gaze from the outside environment. With the HUD, Instrument-panel symbols appear as virtual images at optical infinity, superimposed upon the external scene. The concept has been so successful within the aerospace industry that automobile manufacturers are beginning to implement HUD technologies in automobiles.

The purpose of this study was to evaluate HUD effectiveness in a simulated automobile environment using realistic driving tasks. Twenty male and female subjects with a wide age distribution (19-51) participated. A videotape, taken from the driver's perspective, of a car travelling along a route served as the "scene" that was viewed by each subject. While watching the scene, subjects were required to perform driving tasks related to navigation, speed monitoring, and salient cue detection. Results showed that use of the HUD enabled subjects to respond more quickly to the salient cues, and that more cues were detected when using the HUD. In addition, more speed violations were detected by those subjects using the HUD.

Biography

Russell James Sojourner

(Born: March 10, 1962, Yuma, Arizona)

In 1984 Russell received his B.S. in Behavioral Science from the United States Air Force Academy with an emphasis in Human Factors Engineering. He is currently a Captain in the Air Force.

In 1984 Russell was assigned to Space Division, Los Angeles Air Force Station, California. There he worked for three years as Program Manager for the mission control segment of the Anti-Satellite Weapon, and was responsible for all phases of concept development, design, prototype testing, and production. Emphasis was on training, CRT panel design, and work station layout. While at Space Division, he was awarded two Air Force Achievement Medals, and an Air Force Commendation Medal.

Russell earned an M.S. in the summer of 1989 in Industrial Engineering at North Carolina State University with a specialty in Ergonomics. He is a student member of the Human Factors Society and has served as secretary/treasurer for the North Carolina State Ergonomics Chapter of the Human Factors Society.

Russell is married to Lori Sojourner, and they recently gave birth to a son, James Nathaniel.

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Table of Contents

Page

LIST OF TABLES vi

LIST OF FIGURES vii

INTRODUCTION 1

Background 1
  Accommodation issues 2
Automobile Environment 3
Aircraft Environment 7
Attention Theories 9
  Cognitive capture 11
Summary 12
Objectives 13

METHOD 14

Subjects 14
Apparatus 14
  Videotaped scene 14
  Computer equipment 15
  Viewing screens 16
Subject Tasks 16
  Navigation task 18
  Speed monitoring task 19
  Salient cue detection task 19
Independent Variables 20
  Display configuration 20
  Salient cue location 21
  Road type 21
Dependent Variables 21
  Response time 21
  Navigation effectiveness 22
  Speed violations 22
  Questionnaire 22
Experimental Design 22
  Between subjects factors 22
  Within-subject factors 22
Procedure 23
  Task familiarization 23
  Route memorization 25
  Test session 25

HYPOTHESES 26

RESULTS 27

Salient Cue Detection 27
  Response time 27

Speed Violations 34
Navigation Effectiveness 34
Questionnaire 34

DISCUSSION 36

Salient Cue Detection 36
  Display configuration 36
  Salient cue location 37
  Display x location interaction 38
Speed Violations 39
Navigation Effectiveness 40
Questionnaire Analysis 40
Conclusion...42

REFERENCES 45

APPENDICES 49

  Appendix A. Introduction to the Study 50
  Appendix B. Participant's Informed Consent Form ...52
  Appendix C. Subject Instructions 55
  Appendix D. Map and Directions used in the Route
              Memorization Session 59
  Appendix E. Subject Questionnaire 63

List of Tables

Page

Table 1a. Experimental Design for the Dependent Variable Response Time 24

Table 1b. Experimental Design for the Dependent Variable Speed Violations 24

Table 2. ANOVA on Salient Cue Response Times 28

Table 3. Means and Newman-Keuls Post Hoc Comparisons on Salient Cue Location Response Times 30

List of Figures

Page
Figure 1. Photograph of experimental equipment 17
Figure 2. Display configuration response times 31
Figure 3. Salient cue location response times 32
Figure 4. Location x display interaction 33

INTRODUCTION

Background

The head-up display (HUD) has been a device chiefly employed in tactical aircraft; it enables pilots to view critical flight instrumentation without redirecting their gaze from the outside environment. With the HUD, instrument-panel symbols appear as virtual images at optical infinity, superimposed upon the external scene. Optical infinity is defined as the minimum distance at which the light waves emanating from an image are, for all practical purposes, parallel. This occurs at approximately 6 m. Images at distances greater than this are focused without the need for accommodation. With the HUD, pilots never need take their eyes off the changing visual scene, because the two required sets of visual information (instrument data and external scene) are integrated into one visual field. Because of this, the time taken in redirecting the gaze and refocusing when using conventional instrumentation has been eliminated.

The HUD has been widely accepted within the aerospace industry, as most currently operational tactical fighter aircraft are equipped with HUDs. Their use has also spread to helicopters, various other military aircraft, and even a few commercial airliners (Roscoe, 1987). The concept has been so successful that the automotive industry is beginning to implement HUD technology in automobiles. This is not surprising when the similarities between flying and driving are examined. In either situation, the operator needs to obtain information from sources that traditionally have occupied different visual locations.

Accommodation issues. The problem with conventional display technology rests in the fact that the human eye is limited to 1-2 degrees of maximum acuity corresponding to the foveal region of the retina (Polyak, 1941). Therefore, the operator is unable to obtain detailed visual information from the instrument panel and external scene at the same time. The foveal region also limits where in the visual field conscious attention may be directed, although stimuli in the periphery (to approximately 20 degrees from center) may influence where the foveal region will next be fixated (Carr and Shissler, 1969). In addition to residing in separate spatial locations, the two sources of information are at different focal distances from the operator. The typical dashboard is approximately 50-70 cm from the operator's eyes, while most features in the external scene are at optical infinity.

Because of this distance differential, as the operator switches from one source to the other, he or she must change his or her line of sight while at the same time refocusing the eyes. Weintraub, Haines, and Randle (1984, 1985) have determined that the time required to shift gaze and accommodate causes a measurable increase in an operator's reaction time. Known as accommodative reaction time, many researchers have found that the average time required to change accommodation is approximately 350 ms (Bullimore, Gilmartin, and Hogan, 1986; Tucker and Charmen, 1979).

Naish (1964) found that the transition of visual gaze from head-down (instrument panel) to head-up (external scene) was not just a matter of physical speed, but also of the time needed to change cognitive sets. He argued that the two sources of information vary so greatly in their format and content, that the operator must go through a cognitive process to change mental state from a predisposition toward cockpit information to environmental information, or vice versa. He found that head-down to head-up transitions may take as long as 2-5 seconds, reflecting in large measure the time needed to perceive and react to the visual stimuli in the external scene. This period of time, during which information could be misleading or lost altogether, could well become critical in certain situations.

Automobile Environment

The driver of an automobile must constantly sample the external visual environment, as well as the instrument panel. This time-sharing becomes particularly critical during times of high workload and attentional demand such as may be imposed upon a driver who is navigating through a busy downtown area looking for directional cues while also paying attention to pedestrians, other vehicular traffic, and various traffic signs and signals.

Loo (1978) determined that approximately 90% of all accidental deaths on American highways are due to driver error, compared to only about 10% blamed on vehicular or roadway defects. He also determined that 79% of all accidents in a Canadian city in one year involved such acts as driving the wrong way on a one-way street, or failing to stop or to yield the right-of-way. Some of these incidents may reflect a general failure in perception, such as failure to perceive the traffic sign, vehicle, or pedestrian. Other instances may reflect attention being focused at the wrong point at the wrong time (e.g., at the speedometer instead of the outside environment when the hazardous situation first presents itself). By superimposing dashboard information (speed, warning indicators, etc.) upon the external environment, the need to redirect attention from the changing scene outside the vehicle to the instruments inside is reduced or eliminated altogether.

Driver vision and perception is the key variable in the driver-vehicle-road system. Hills (1980) has estimated that over 90% of all information input to the driver is visual. He also noted that there are over six million accidents per year in the U.S. attributable to not allowing enough headway. Headway is defined as the time elapsed before a trailing car reaches a point just passed by a lead car.

Based on the short headway times generally adopted on the road, it would appear that many drivers assume they will not have to make an unexpected emergency stop. This may give the false sense that frequent glances away from the vehicle in front can be made without serious consequence. As mentioned earlier, the foveal region defines where in the visual field conscious attention may be directed. Thus, while gaze is directed at the instrument panel, cues in the periphery may be responded to more slowly or lost altogether.

Zwalen and Debald (1986) have asserted that a driver requires an almost continual series of eye fixations upon the road ahead in order to maintain proper lateral position of the automobile. In the case of city driving at 30 mph, if a driver takes 2.0 s to fixate upon a display within the automobile, there is approximately a 1.25% chance that the automobile will deviate out of the lane. With 4 and 6 seconds of non-environment fixation, the chances of deviating from the lane increase to 6.30% and 18.14%, respectively. These data indicate that a HUD may be very useful in keeping the eyes directed toward the roadway scene, reducing the probability of a hazardous lateral lane deviation. However, these data are based upon driver responses when forced to direct attention continously away from the roadway scene. Typical driving behavior involves a visual time-sharing of attention to the roadway, the displays, and a variety of distracting stimuli. For example, it has been shown (Dingus, Antin, Hulse, and Wierwille, 1986) that in the performance of complex in-vehicle tasks while driving, the average time per glance (i.e., to a particular display or control panel) remained relatively constant while the total task time increased.

A display located at optical infinity might also benefit older drivers, because the speed and extent of accommodation decrease with age due to the onset of presbyopia. Sauter and Kercheart (1972) discovered that older drivers exhibited a higher refixation time when switching from the road to a target on the instrument panel than did younger drivers. This age-related disparity could be eliminated if accommodation and redirection times were eliminated through use of a HUD.

Rutley (1975) showed that drivers adhered to the posted speed limit more closely when using a HUD than when using a conventional speedometer. Rutley concluded that this was due to an increased awareness by the driver of his or her actual speed, since it was viewed almost continuously, without added effort or redirection of the gaze.

These studies provide evidence that the HUD concept is a good one for use in automobiles. It appears that superimposing the two sources of needed visual information can increase awareness of salient stimuli in the outside world, even while the driver is attending to displayed information.

Aircraft Environment

Since automobile manufacturers have begun to place HUDs in automobiles, it is important to evaluate the automobile HUD from a human factors perspective. Because the automobile HUD is a novel idea, research has been limited; the aerospace industry, on the other hand, has significant experience with HUD technology. Issues relevant to the automobile environment that can be gleaned from HUD research in aircraft will be discussed next.

In most direct experimental comparisons the HUD has proven superior to a conventional instrument-panel layout in relation to a variety of both performance and subjective measures. Fischer (1979) found that pilots were able to efficiently identify their destination airport, and the presence or absence of air traffic when using a HUD. Haines, Fischer, and Price (1980) found that HUD use led to fewer look-up and look-down transitions, and that the HUD permitted smoother engine power changes (that is, fewer changes of usually smaller magnitude). Weintraub, et al. (1984) state that the HUD has consistently proven superior using virtually every performance measure, and that pilot questionnaire data show a strong preference for HUD technology.

The aircraft HUD has the inherent benefits mentioned earlier: increased pilot awareness of the outside environment, lowered reaction times, and reduced need to shift gaze and reaccommodate. In some instances however, the HUD has proven to be detrimental. Fischer, Haines, and Price (1980) found that two pilots missed seeing an obstruction on their landing runway when using a HUD, while no pilots missed the obstruction when using conventional displays. Weintraub, et al. (1985) showed that pilots using a HUD needed more time to decide if their landing runway was closed or not.

Recently, some researchers have questioned the utility of using infinity optics for HUD symbology. Iavecchia, Iavecchia, and Roscoe (1988), and Roscoe (1987) have reported that collimated images do not necessarily cause the eyes to focus at optical infinity. Rather, they claim collimation forces the eyes to focus around the dark focus point, which is generally much closer than the nearest point of optical infinity. The bold symbology of HUD displays further exacerbates the problem by not requiring sharp focus for legibility. If the above findings are correct, and the eyes do not focus at optical infinity when using the HUD, the consequence is the inability of the user to attend to both the display and distant objects concurrently. Roscoe (1987) claims this results in spatial disorientation and losses of distance acuity.

Other researchers disagree with the above findings. Newman (1987) has stated that pilots mention no accommodation difficulties or disorientation during HUD use. He has further reported that raindrops and spots on the windshield often force the eyes to focus on the windshield, but that HUD symbology allows the eyes to focus further out, thereby enhancing visual performance. Weintraub (1987) has reported that HUD infinity optics should favorably attract accommodation toward far focus, not dark focus.

Attention Theories

Failure of the HUD to provide consistently superior performance centers around the human's ability to attend to (i.e., perceive and make effective use of) two complex sets of information presented simultaneously in the same visual field. The literature reflects two basic types of theories: (1) the human is a single channel processor, and therefore information is processed sequentially (Broadbent, 1958); (2) the human has a multi-channel capacity and is capable of parallel information processing (Deutsch and Deutsch, 1963).

These theories predict different degrees of effectiveness when superimposing two different sets of information. If the human cannot process two sets of information in parallel, then even if a display were superimposed on the outside world, the operator could only attend to one source or the other. The other theory would support superimposition, since some amount of parallel processing could be accomplished.

Wickens (1984) has pointed to recent research which suggests that parallel processing can be accomplished within a given channel of information. A channel may be quite specific, like a particular dial, or a channel may take on a broader interpretation, such as a visual location in space.

An experiment by Neisser and Becklen (1975) indicates that even superimposed information, however, may be interpreted as more than one channel. Their subjects watched a display in which two video games were presented simultaneously, one superimposed over the other. One showed distant figures tossing a ball, the other showed a hand-slapping game. One game was designated as "relevant", and critical elements were to be monitored and detected. It was found that while monitoring one game, subjects failed to see events in the other game, even if the event was novel or unusual. In this regard, Wickens (1984) has suggested that "separation" of channels may be defined not only in terms of differences in spatial or retinal location, but also in terms of the nature of the perceived activity or possibly the perceived distance from the observer.

Another important factor relating to the allocation of attention might be the complexity of the information within the channels. Dual task theory suggests that parallel processing might be possible if the two sets of information are relatively simple, while complex displays may hinder parallel processing (Kantowitz, 1983). This has implications in HUD design, since relatively simple and uncluttered displays may not compete for attentional resources in the same manner that a sophisticated navigational display might.

Cognitive capture. The discussion of attention and parallel processing raises a significant question with respect to HUDs. They were designed to ensure that information inside and outside the cockpit could be processed simultaneously. It appears that this may not be the case, and pilots may actually treat the two sets of information as separate attentional channels. A pilot might, for example, become engrossed in processing instrument information while ignoring critical cues from the outside environment (Wickens, 1984). Weintraub (1987) has labeled this phenomenon "cognitive capture" and has indicated that this may be the most compelling concern when considering HUD technology.

Cognitive capture may have surfaced in the study conducted by Fischer, et al. (1980). In this experiment commercial pilots performed landings using a HUD in a fixed-base 727 simulator. Of eight pilots tested, two missed seeing another object on their landing runway when using the HUD; none missed the object when using conventional instrumentation. Further complicating the HUD's use was the fact that its central symbols obscured the runway obstacle to a large degree. Upon seeing the tapes during their individual debriefing session, both of the pilots who had previously missed the object expressed surprise and concern that they had missed such an obvious target. A further point of concern with this study was that the response time for the pilots who did see the object was three times slower when using the HUD than when using a normal instrument panel.

Summary

The HUD has been designed to aid the vehicle operator in scanning instrument information and the information in the outside environment. Its use allows the operator to avoid any need to take his or her eyes off the changing scene ahead. This saves time normally taken in changing visual gaze and reaccommodating. The HUD has been extremely well accepted in the aerospace industry, and in most cases, pilots using the HUD perform better than when using a conventional instrument panel.

There have been some studies, though, that have shown that the HUD could have a detrimental effect on performance. These results are generally attributable to some combination of the following hypotheses: (1) the human operator can process only one stimulus at a time, and may spend time switching cognitive sets from the HUD to the external environment; (2) the phenomenon of cognitive capture, wherein the HUD becomes too compelling to the pilot, and attention is diverted from the environment even though vision is still directed there. Note that this may be a more serious problem with the HUD than with conventional panels, because the HUD may lull the user into a false sense of security (i.e., he or she thinks the events in the outside environment are being sufficiently monitored when they are not), and (3) the HUD symbols may actually obscure critical events in the environment.

Objectives. As mentioned earlier, there are many similarities between automobile driving and aircraft flying in terms of visual information and attentional demands. The objectives of this study are to address several of the following questions: (1) Will the HUD benefit drivers as much as it benefits pilots? (2) Will use of the HUD help prevent collisions by allowing the driver to remain focused on the roadway environment or will the previously mentioned drawbacks surface? (3) Will the HUD facilitate use of instrument panel data (e.g., speedometer)? The automobile studies to date are incomplete and further research is needed. Variables such as response time and missed visual cues need to be examined in the context of realistic driving tasks.

METHOD

Subjects

Twenty subjects volunteered to participate in the study for pay at the rate of $5.00/hr, and every subject was a currently licensed driver. In addition to being able to see well enough to be licensed to drive, each subject was further tested with a Titmus Industrial/Occupational Vision Tester to insure that his or her corrected far visual acuity was at least 20/40.

All subjects reported no extensive driving experience in the northern portion of Durham, N.C. This was necessary as one of the main subject tasks performed in the study was to engage in navigation behaviors in an area equally unfamiliar to all subjects.

Subjects were divided into two equal groups. Each group consisted of five males and five females, with ages ranging from 19 to 51. The average age of one group was 29.5 years, and the average age of the other group was 30.5 years.

Apparatus

Videotaped scene. A videotape, (as seen from the driver's perspective) served as the "scene" to be watched by each subject. The videotaped scene was recorded with a Hitachi video camera mounted on the driver's side headrest. The camera was equipped with a 46mm lens, and provided a clear and precise video image of the external scene. The camera was pointed straight ahead, and the lens was approximately located at eye level.

The videotaped scene was comprised of three road types: two-lane rural, four-lane highway, and four-lane city. The two-lane rural section was five miles long and lasted six minutes, the four-lane highway section was six miles long and lasted seven minutes, and the four-lane city section was six miles long and lasted eleven minutes.

Two videotapes of the route were recorded: one used as a training aid to help the subjects memorize the specified route, and one that served as the actual test scene. The two videotaped scenes were recorded one after another. A third separate videotaped route was used as a tool to aid in task familiarization. Two VCRs were used to playback the videotapes.

Computer equipment. An Amiga 1000 computer was used to produce a simulated digital speedometer. The Photon Paint software by Micro Illusions produced the graphical images, and the Director sotware by The Right Answers Group sequenced the numbers. The computer also generated the "salient cues" which were novel stimuli appearing within the external environment. Each such cue had to be perceived, correctly identified, and quickly and accurately responded to. The salient cue was designed to look like a ball, and subjects were instructed to consider it as a potential hazard in the roadway. The ball was green in color, measuring 49 min in diameter. The Genlock Module (an Amiga peripheral hardware device) allowed the graphical images to be superimposed onto the video image of the test route, simulating a HUD.

Viewing screens. A 180 cm (71 in) Sony projection television provided the viewing screen upon which the video and graphical images were projected. It was located approximately 3 m from each subject, and the screen luminance ranged from 62-69 nits. The television was chosen for its large size in order to occupy a large portion of each subject's field of view (29 degrees), therefore providing a more realistic simulation of what a driver actually sees. The Amiga monitor served as the dashboard display. The experimental equipment layout is shown in Figure 1.

Subject Tasks

The subjects performed the following tasks concurrently during the test session to simulate key cognitive and perceptual aspects of the driving scenario: navigation, speed monitoring, and salient cue detection. The salient cue detection task served to evaluate the effects of the display configurations on the driver's ability to detect potentially hazardous situations occurring in the outside environment. The navigation and speed monitoring tasks were chosen to simulate two of the key cognitive demands on the driver of an automobile, and to see the effects of the

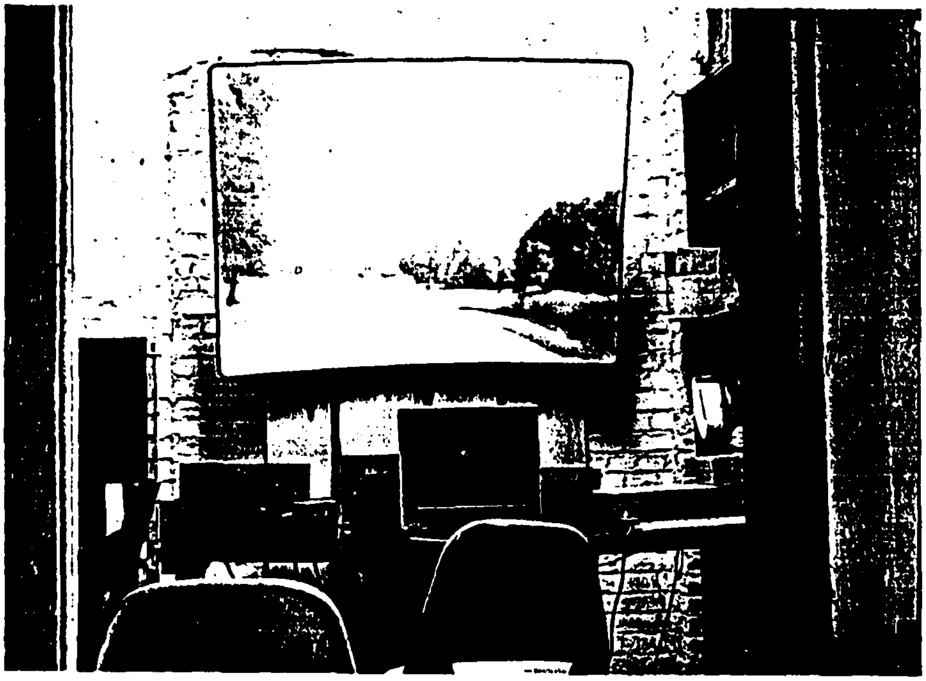

Figure 1. Photograph of experimental equipment.

experimental conditions on performance of these tasks. These latter tasks also served the crucial function of assuring that the subjects did not monitor salient cues at the expense of the more primary driving tasks of speed monitoring and navigation. Further, the three tasks together served to insure that the driver did not simply ignore any of the important sources of information (i.e., the external scene or the dashboard display), since in an actual automobile it is important to perform all of these tasks concurrently.

Navigation task. The test route closely approximated the training route memorized by the subjects, but it differed in that there was one navigation error in each of the three road types. A navigation error was defined as any discrepancy between the training route and the test route. Throughout the test route there were dozens of opportunities for navigation errors, and it was the subject's task to observe the progression of the automobile, and verbally indicate when an incorrect turn had been made, or when a correct turn was missed. For example, if the training route called for a left turn, and the test route showed the automobile making a right turn, the subject was required to say, "wrong turn, the car should have made a left." When a navigation error was committed, the vehicle made a corrective action to return to the training route. The navigation errors committed in the test route included a wrong turn, a wrong highway exit, and a missed turn. By performing this task, a cognitive and visual task were combined, forcing the subject to pay careful attention to the roadway, much like the subject would be doing when navigating to a specified destination in an actual driving scenario.

Speed monitoring task. Another task was to verbally report each occurrence of the indicated speed exceeding 5 mph over the posted speed limit. The speedometer closely matched the speed of the vehicle, so visual cues from the environment could be used in a realistic fashion to aid in determining when a speed violation was being committed. The speedometer indicated three speed violations per road type, and each violation occurred at a pre-determined random time within the specific road type. A speed violation lasted three seconds, and the subject reported a speed violation by saying, "speeding."

Salient cue detection task. The subject was also instructed to respond to any salient cues that occurred in the external environment. The cue appeared to be in the roadway, a few feet in front of the vehicle. The subject was required to depress the mouse button whenever the cue appeared. He or she was told that the cue would appear at random, and that the button should be pushed as soon as possible to avoid a "hazardous situation." This was analogous to depressing the brake pedal. Depressing the mouse button caused the cue to disappear. If no response had been made within three seconds, the cue disappeared spontaneously.

Independent Variables

The independent variables were (1) display configuration, (2) salient cue location, and (3) road type.

Display configuration. Typical dashboard information was represented with a digital speedometer viewed in one of two configurations depending on experimental condition--either superimposed on the test scene (HUD), or displayed on the dashboard monitor (dashboard). In the HUD condition the numbers were 1 deg 20 min in height, superimposed on the test scene at eye level in front of the driver, appearing slightly above the hood level of the automobile. They were dark blue in color, thereby providing a good contrast with the videotaped scene. The numbers and scene were projected on the large screen television.

In the dashboard condition the speedometer numbers were 1 deg 13 min in height, also blue, and they alone were displayed on the Amiga monitor. The monitor was situated 50-70 cm away from subject, and specific distance varied since each subject was allowed to comfortably position his or her chair, as would be done in an actual automobile. The speedometer numbers were displayed approximately 20 degrees below the horizontal line of sight. The test scene was once again projected onto the large screen television.

In both conditions, the large screen television was approximately three meters from the subject. In the HUD condition the superimposition of the speedometer and scene produced two images located at the same optical distance from the subject. In the dashboard condition, the subject's eyes were forced to reaccommodate when gaze was shifted from the dashboard speedometer to the test scene (1.7 diopters for the dashboard display to 0.3 diopters for scene--compared to 0.0 diopters for optical infinity).

Salient cue location. The salient cue occurred at three different locations in the roadway: left, center, and right. The center location was defined as the horizontal center of the projection television. The left cue appeared 9 deg 30 min to the left of center, and the right cue appeared 9 deg 30 min to the right of center. It was displayed three times during each road type, once for each of the three locations. The time of cue presentation within each road type was randomly chosen.

Road type. As stated earlier, there were three different road types travelled in the route; two-lane rural, four-lane highway, and four-lane city.

Dependent Variables

The dependent variables were (1) response time to the salient cues, (2) navigational effectiveness, (3) speed violations reported, and (4) questionnaire responses.

Response time. Response time was recorded for the cue detection task. This was defined as the time from introduction of the salient cue until the time the subject depressed the mouse button. This was compared across conditions to analyze how well the subjects perceived and responded to salient cues using the different display configurations. In addition, response times were compared across the different cue locations.

Navigation effectiveness. The number of incorrect decisions regarding navigation was used to determine whether a subject had been effectively paying attention to the navigational task. If a subject either reported a navigation error when none had been committed, or missed an error when one had been committed, it was scored as an incorrect decision.

Speed violations. The number of correct speed violations detected were recorded for each subject, and were compared across display configurations and road types.

Questionnaire. A questionnaire was used (see Appendix E) to gather the subjective opinions of each subject regarding various aspects of the experiment. Also, this information provided insight into user preferences with regard to HUD use.

Experimental Design

Between subjects factors. Subjects were grouped based on display type: (1) HUD, and (2) dashboard.

Within-subject factors. There were two within-subject factors: (1) salient cue location, which had three levels: left, center, and right; and (2) road type, which had three levels: two-lane rural, four-lane highway, and four-lane city. The experimental designs are illustrated in Tables 1a and 1b.

Procedure

All subjects first read an introduction to the study (Appendix A). They then read and signed an informed consent form (Appendix B); signing this form indicated they knew and understood their rights as voluntary participants in the study. The subject's visual acuity was checked, and a list of instructions describing the required tasks was read by the subject (Appendix C).

The study consisted of three sessions: task familiarization, route memorization, and test.

Task familiarization. This session began with the subject sitting behind the dashboard speedometer monitor. He or she was instructed to treat the monitor as though it were the dashboard in his or her own car, and to position the seat accordingly. During this session the subject became familiar with the equipment and experimental tasks by performing a short version of the test session. A five minute videotape that contained two speeding violations, one navigation error, and two salient cue occurrences was viewed by each subject. This videotaped route was recorded on a different set of roads than those seen in the training and

Table 1a

Experimental Design for the Dependent Variable Response Time

		Salient Cue Location		
		Left	Center	Right
Display Configuration	HUD	S_{1-10}	S_{1-10}	S_{1-10}
	Dash	S_{11-20}	S_{11-20}	S_{11-20}

Table 1b

Experimental Design for the Dependent Variable Speed Violations

		Road Type		
		Rural	Highway	City
Display Configuration	HUD	S_{1-10}	S_{1-10}	S_{1-10}
	Dash	S_{11-20}	S_{11-20}	S_{11-20}

test videotapes. Each subject was required to perform all tasks satisfactorily before moving on to the next session. Satisfactory performance was defined as proper verbal reporting when the navigation error was committed and the speed violations were displayed, and correct mouse depression when the salient cues appeared. All subjects exhibited satisfactory performance during this session.

Route memorization. During this session the subject was given a set of instructions and a map depicting the correct test route (see Appendix D). Each subject was required to spend as much time as needed to memorize the route. This usually took from five to ten minutes. Once memorized, the subject was required to correctly recite the route from memory. If this could not be done correctly, the errors were pointed out, and the subject had to recite the route correctly again. Next, the training route (no navigation errors) was shown to each subject, and he or she was asked to simply observe the route. By watching the proposed route, each subject was able to become familiar with environment, further enhancing the memorization process.

Test session. The last session required the subject to watch the videotaped test route (including navigation errors) while performing the three concurrent driving tasks. This session lasted approximately 24 minutes.

HYPOTHESES

It was expected that use of HUD technology would result in better performance for all dependent measures when compared to the standard dashboard. More speed deviations and salient cues would be noticed, and response time to these cues would be less when using the HUD. The above hypotheses were based on the fact that a subject's eyes would never have to leave the external scene to gather important information. Since all three information sources (speedometer, salient cues, navigational cues) would be within the same field of view, performance would be facilitated on all three tasks.

RESULTS

Salient Cue Detection

The intent of this analysis was to determine how display configuration and cue location affected subjects' response times to the salient cues. It is important to note that a small windshield chip was present near the center cue location, and this may have influenced the detection of center cues. This is unlikely, however, as all subjects were informed about the chip, it was considerably smaller than the salient cue, and there were no errors of commission (depression of mouse when no cue was present).

Nine salient cues were presented to each subject, three in each location in the scene. Response times were averaged for each position, resulting in three response times per subject.

Subjects using the HUD missed a total of three salient cues, while subjects using the dashboard display missed a total of nine salient cues.

Response time. An analysis of variance (ANOVA) was performed to determine how response time was affected by display type and salient cue location. The ANOVA on response time showed display configuration and salient cue location to be significant. A summary of the results appears in Table 2.

An analysis of the means showed that mean response time when using the HUD was significantly less than when using

Table 2

ANOVA on Salient Cue Response Time

Source	df	Sum of Squares	F	p
Between Subjects				
Display (D)	1	3.93	22.26	0.0002
Sub	18	3.18		
Within-Subject				
Location (L)	2	2.65	13.99	0.0001
L x D	2	1.46	7.69	0.0017
L x Sub	36	3.41		
Total	59			

the dashboard display. A plot of the response times appears in Figure 2. Inspection of this figure shows a more compact concentration of response times around the mean in the HUD condition, and a clear shifting of the response times downward, relative to the dashboard condition.

The post hoc analysis of cue location means showed that the mean response time to the center cue was significantly less than the mean response times to the other two cue locations (means and standard deviations are listed in Table 3). A plot of the response times appears in Figure 3. The center location had a more concentrated distribution of means, and was shifted noticeably downward. The other two locations produced similar results to each other.

The ANOVA in Table 2 also shows that the location x display configuration interaction was significant. This is depicted graphically in Figure 4.

It is important to note that for this analysis a missed cue was conservatively recorded as the maximum response time (3 s), and the response times per location were computed accordingly. This yielded an analysis that took into consideration the missed cues. A second analysis was performed omitting these response time data associated with the missed cues. The mean response time for the HUD condition excluding the missed cue data was 0.57 s, and for the dashboard condition the mean response time was 1.01 s when the missed cue data were omitted.

Table 3

Means and Newman-Keuls Post Hoc Comparisons on Salient Cue Location Response Times

	Cue Location		
	Left	Center	Right
Means	1.097 (A)	0.611 (B)	1.002 (A)
st dev	0.630	0.182	0.446

Means with the same letter are not significantly different (__= 0.01).

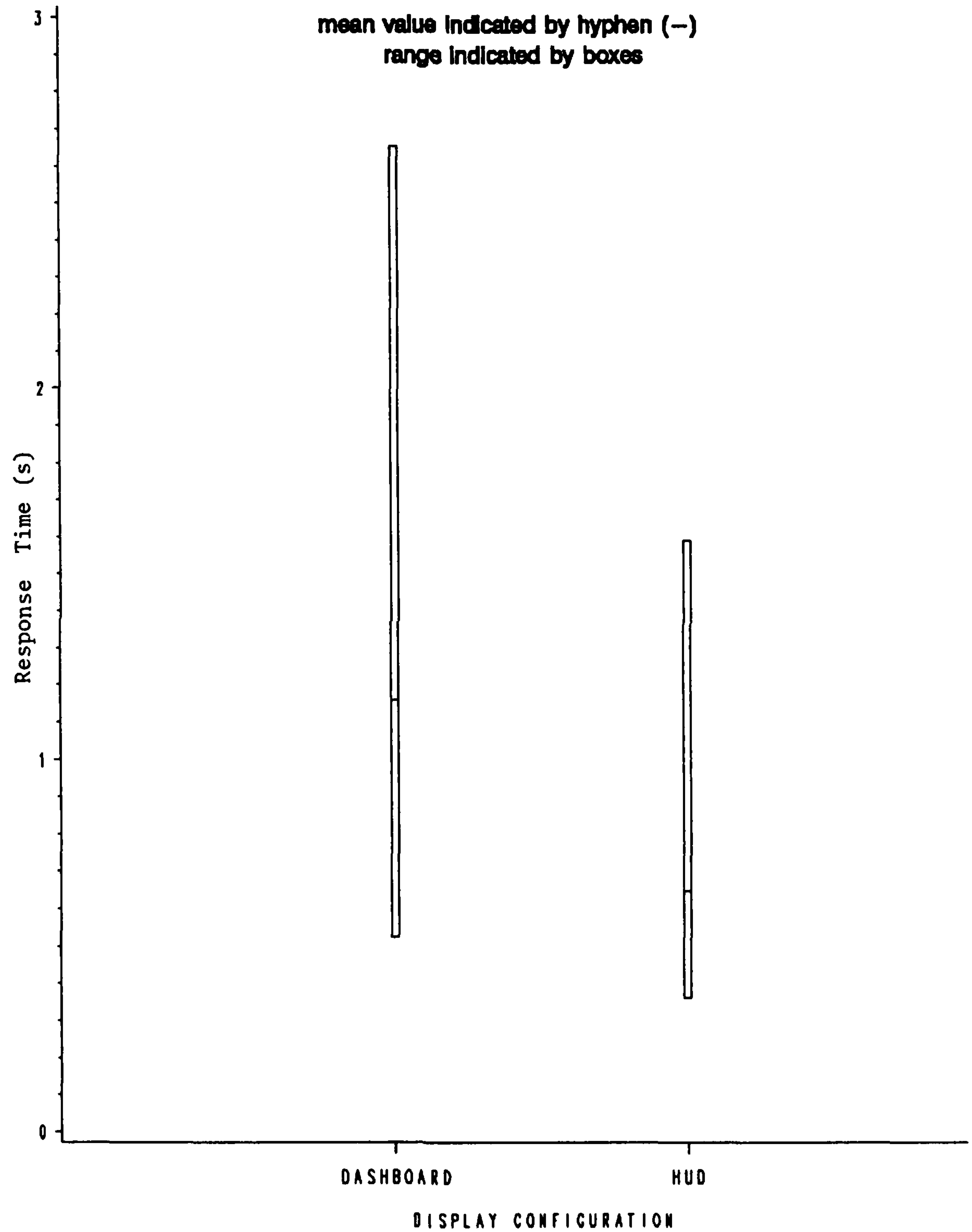

Figure 2. Display configuration response times.

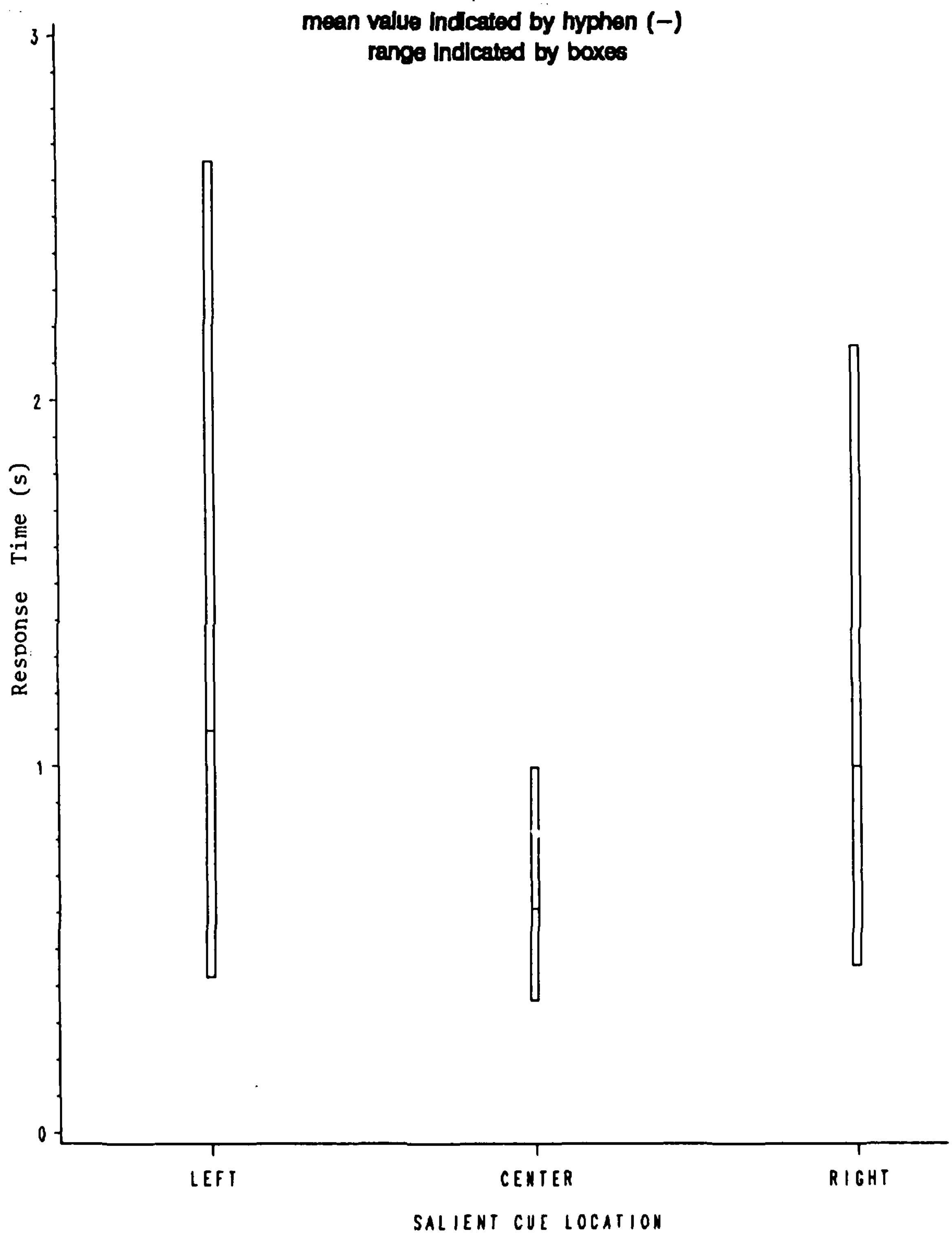

Figure 3. Salient cue location response times.

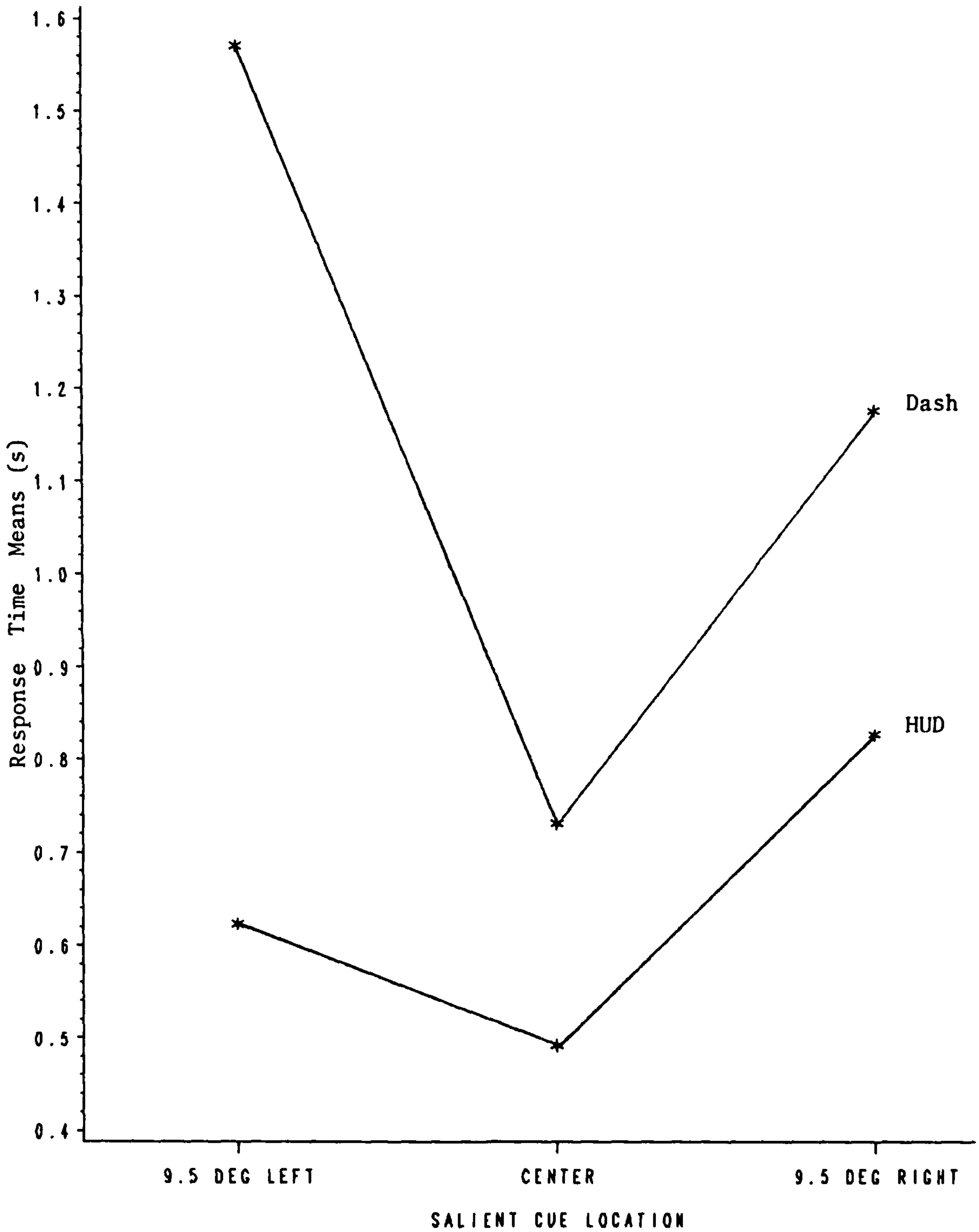

Figure 4. Location x display interaction.

Speed Violations

No statistical analysis was performed on speed violations due to the small number of missed violations. Subjects in the HUD condition detected 100% of the total of 90 speed violations, while the subjects in the dashboard condition missed 7 out of the 90 total. Furthermore 5 out of the 10 subjects in the dashboard condition missed at least 1 speed violation.

Navigation Effectiveness

Only three navigation errors were committed across all subjects and conditions in the study: one in the HUD condition and two in the dashboard condition. These results indicate each subject was paying close attention to the roadway and the progression of the vehicle.

Questionnaire Analysis

Each subject was asked if he or she would consider owning an automobile that displayed instrument information on the external scene. Seven subjects reported that they would, and three reported they would not.

The HUD symbology was not perceived as effective in aiding performance on the three test tasks. When asked if the placement of the speedometer numbers aided in performance of the tasks, subjects could mark anywhere on a scale ranging from -5 (hindered greatly) to 5 (helped greatly), see Appendix E. The mean effectiveness rating was 0.37 (standard deviation of 0.72) for the navigation task, and -0.22 (standard deviation of 1.85) for the salient cue detection task. For the speed monitoring task, the results were mixed, as 6 individuals felt superimposition of the numbers aided in performance, while 4 felt that a normal dashboard configuration would be better.

When asked if they liked having the speedometer displayed on the external environment, a scale was used ranging from -5 (disliked much) to 5 (liked much). The rating was 0.57, and the standard deviation was 3.22.

Common criticisms of the HUD concept included: (1) tendency to focus on the numbers at the expense of the environment; (2) changing environmental contrast made the numbers difficult to see in some situations; and (3) the numbers, placed in the primary line of sight, obscured objects in front of the automobile.

DISCUSSION

Salient Cue Detection

Display configuration. Use of the HUD digital speedometer enabled subjects to respond more quickly than did a conventionally located speedometer to a potentially hazardous situation (the salient cue). Subjects using the HUD had an average response time of .65 seconds (standard deviation of .30), while subjects using the dashboard had and average response time of 1.16 seconds (standard deviation of 0.53). This equates to reacting 510 ms quicker when using a HUD. The fact that the HUD subjects never needed to take their eyes off the changing visual scene seemed to enable them to detect and respond significantly more quickly when a salient cue was presented. Moreover, subjects using the dashboard display were required both to shift gaze, and to reaccommodate (from 0.3 diopters to 1.7 diopters) when shifting between scene and display.

Practically speaking, the difference in response times could very well have significant implications. If the same delay (510 ms) were to occur in an actual car travelling at 45 mph, this would result in travelling 34 additional feet before the driver were to perceive the hazardous situation. For a car travelling at 65 mph, the delay would result in an extra 50 feet travelled.

An extension of this type of analysis can be performed when looking at missed cues. Three cues went undetected by the subjects using the HUD. In the dashboard condition nine cues went undetected. Subjects using the dashboard speedometer missed three times as many salient cues as subjects using the HUD, and this fact may be quite important in a real driving situation where the salient cue might be a ball, a pet, or a child.

Salient cue location. The salient cues presented in the center position were responded to significantly more quickly than those in the other two locations. This is not surprising, as the center cue was approximately located in the subject's direct line of sight. It is important to note that in neither condition was the salient cue obscured in any way. The two peripheral cues were responded to at approximately the same average speed. The center cue was easily noticed and responded to, resulting in a compact distribution of individual reaction times. The peripheral cues showed a much more dispersed distribution. This was a result of some cues being easily detected and responded to, while others remained in the scene for considerably longer periods before a response was made. These results are consistent with past research on vision where items in the periphery do not always attract conscious and immediate attention. Inspection of missed cues support this idea, since no center cues in either condition were missed. The subjects in the HUD condition missed three right cues, while the subjects in the dashboard condition missed three right cues and six left cues.

Display x location interaction. Inspection of Figure 4 reveals that the display x location interaction was caused primarily by the responses to the left salient cue. For the subjects using the dashboard speedometer, responses to the left cue were considerably slower than the responses to all other cue positions in either display configuration. It is believed this took place because of the nature of the external scene viewed by drivers. Subjects in this study were instructed to monitor vehicle speed and compare it to the posted speed limit. Since they were observing an unfamiliar route, monitoring the posted speed limit signs took considerable attention, directed at the right side of the environment where the speed limit signs were posted.

The data on missed cues further supports this notion, as six of the nine missed salient cues in the dashboard condition were left side cues. This effect was not seen in the HUD condition, as the exclusive head-up posture allowed those subjects to remain more aware of the changing visual scene in the entire field of view.

The full implication of these findings is unclear. Results are consistent with those of display configuration, in that at every location, the HUD subjects responded more quickly. Further, as may be expected in a real world driving scenario, the operator of the vehicle may tend to be more aware of events directly in front of him or her, and less aware of peripheral actions. The fact that the left side cues in the dashboard condition were responded to inordinately slowly may be an artifact of the research setting. In a real world situation, the driver may not be striving for as high a level of speed monitoring performance as was seen in this study. This may result in less attention being paid to every speed limit sign, allowing a more equivalent visual sampling of the environment, and possibly more similar response times to all salient cue locations.

Speed Violations

All subjects performed well on the speed monitoring task. No speed violations were missed by the subjects using the HUD, while seven were missed by the subjects using the dashboard. It appears the HUD allowed subjects to be consistently more aware of vehicle speed than did the dashboard monitor. This is attributable to the fact that the speedometer numbers were continually observable by the subjects using the HUD, as opposed to the subjects using the dashboard who sampled the speedometer at their own discretion. Not only were 7 speed violations missed by the dashboard subjects, 50% of the dashboard subjects missed at least 1 violation. It is clear that superimposition of the speedometer numbers in the HUD condition allowed the subjects a more consistent monitoring of vehicle speed. These findings are consistent with those of Rutley (1975) who showed that drivers adhered to the posted speed limit more closely when using a HUD due to increased awareness of actual speed. The HUD may therefore be a useful aid in allowing drivers to more closely maintain their desired speed.

Navigation Effectiveness

There was little variability in navigation task performance. The consistently high level of performance indicated that subjects were paying close attention to the roadway, providing a meaningful and unconfounded analysis of salient cue detection performance.

Questionnaire Analysis

There was an overall level of indifference regarding HUD use and perceived effectiveness. Subjects believed the HUD was ineffective in aiding the navigation and salient cue detection tasks, and they were split as to whether it helped in monitoring vehicle speed. This is quite surprising considering the results previously discussed. This phenomenon can be partially attributed to the novelty of the device. All the subjects were used to performing traditional tasks in their own automobiles. Years have been spent using one type of display configuration, and the HUD concept was entirely foreign. Support for this notion derives from the fact that many subjects reported feeling more comfortable with the HUD concept as the study progressed. Furthermore, although the subjects did not see the benefit of the HUD, seven of the ten subjects were intrigued enough that they would consider owning an automobile equipped with one.

A common observation made by the subjects was that the HUD symbology made it difficult to concentrate on the environment, and that performance on the salient cue detection task suffered because so much attention was focused solely on the speedometer numbers. In fact, although attention may have been drawn to the display speedometer, it appears that the operator may posses the ability to divide attention among several stimuli. The fact that the driver's gaze never needed to be shifted allowed a partial sharing of attention between the display and the environment. In this way, performance on both the speed monitoring and salient cue detection tasks was enhanced.

A number of criticisms raised by the subjects were informative. As mentioned above, subjects felt they did not sample the environment enough because too much attention was focused on the HUD speedometer. It is believed that if drivers were informed of the benefits of HUD use, and were shown that performance was actually enhanced, that this reservation may be reduced.

To reduce the need to focus on the displayed speedometer, many subjects also suggested the numbers be moved out of the primary line of sight. This solution would force a compromise between their preference and the basic

HUD concept. It appears the HUD concept is a good one, and moving the display more to the periphery may reduce some of its advantages. On the other hand, reaccommodation would still be eliminated, the magnitude of the gaze shift would be less than with a conventional dashboard display, and subject preferences might be better served.

One other common criticism concerned the color of the HUD speedometer. Many subjects complained that changing environmental colors created poor contrast, making the numbers difficult to see in some instances. The experimental equipment contributed to some contrast difficulties, as the videotaped superimposed numbers were not as legible as would be encountered in an real driving scenario using an actual virtual image.

Conclusion

Performance by subjects using the HUD proved superior to performance by those subjects using the dashboard display. More speed violations and salient cues were detected, and the average response time to the salient cues was less when using the HUD.

The HUD allowed subjects to perform all three required tasks without ever shifting their eyes away from the external scene to gather important information. Therefore, the three visual information sources being attended to (speedometer, salient cues, and navigational cues), all being in the same field of view and focused at the same optical distance, facilitated performance on the three tasks. In addition, although subjects using the HUD expressed indifference as to its effectiveness, the majority would consider owning a HUD-equipped automobile in the future.

Due to the infancy of automobile HUD research, future studies could take many directions. The next logical step would be to perform a similar study utilizing actual driving behaviors and a real automobile HUD. Future considerations should also include HUD design details such as color, size, font, and location. It is interesting to note that current automobile manufacturers do not agree as to the proper placement of HUDs in their cars. Some companies are placing the HUD in the direct line of sight, while others are using the lower corner of the windshield. These types of factors need to be examined not only from a performance standpoint, but from a consumer satisfaction standpoint as well. A further topic of investigation involves the complexity of the display. Since the only the information presented in this study was a digital speedometer, continued research should include more complex displays in order to determine whether complex information can also be successfully displayed in the HUD format. Complex display systems such as moving map navigational aides should be considered for inclusion.

Another topic of future research involves time on task.

A longer test duration may result in subjects either ignoring the display, or becoming mesmerized by it (solely monitoring the display at the expense of monitoring the external environment).

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APPENDICES

Appendix A. Introduction to the Study
Appendix B. Participant's Informed Consent Form
Appendix C. Subject Instructions
Appendix D. Map and Directions used in the Route Memorization Session
Appendix E. Subject Questionnaire

Appendix A. Introduction to the Study

INTRODUCTION TO THE AUTOMOTIVE STUDY

The purpose of this study is to evaluate driver behavior using a simulated driving task. The work is being conducted by Russell Sojourner, who is a graduate student in Industrial Engineering under the direction of Dr. Jon Antin, assistant professor of Industrial Engineering, at North Carolina State University.

In this study you will be observing a videotape, taken from the driver's perspective, of a car travelling along a route in the Durham area. You will be asked to perform various tasks commonly done while driving; such as monitoring vehicle speed, watching for potential hazards in the roadway, and performing a navigation behavior.

Upon completion of your participation in this study, you will be paid at the rate of $5.00 per hour. If during the study you feel that you are unable to continue, you are free to end your participation at any time and immediately withdraw your data; you will be paid at the previously stated rate for your participation up to this point.

Please do not hesitate to ask questions regarding this study or your participation in this study. The experimenter will be more than willing to answer any of your questions. However, in order to avoid biasing the results, answers to certain questions may be delayed until your participation is complete. Also, we ask that you not discuss the details of the study with anyone for a period of two months.

Appendix B. Participant's Informed Consent Form

PARTICIPANT'S INFORMED CONSENT

1. You are being asked to volunteer to be a subject in a research project whose purpose and description are contained in the document "introduction to the Automotive Study", which you have already read.

2. The data gathered in this experiment will be treated with anonymity. Shortly after you have participated, your name will be separated from your data.

3. You should know that at any time you are free to withdraw from participation in this research program without penalty. You will be paid at a rate of $5.00 per hour for the time you actually spend. Payment will be made shortly after you have finished your participation.

4. Signing this consent form does not in any way limit your rights. It confirms that your participation is informed and voluntary.

5. Signature of volunteer and date:

I have read and understand the scope of this project. I hereby give my consent to participate, but I understand that I may withdraw myself and my data at any time if I choose to do so.

Signature ______________________________

Date ______________________________

6. Signature of experimenter and date:

Signature ______________________________

Date ______________________________

7. Signature of witness and date:

Signature ______________________________

Date ______________________________

Appendix C. Subject Instructions

INSTRUCTIONS

In this study you will be performing a simulated driving task. You will be observing a videotape, taken from the drivers perspective, of an automobile travelling along a specific route in the Durham area. While watching this videotape, you will be asked to perform various tasks normally associated with driving.

The study will consist of three sessions: task familiarization, route memorization and driving.

Task Familiarization Session:

In this session you will become familiar with the experimental equipment and the tasks which you will be performing in the driving session (discussed in detail later). You will be watching a short videotape to aid in this familiarization.

Route Memorization Session:

In this session, you will memorize a specific route. You will be presented with a map and a list of instructions. Study this information carefully and commit it to memory. In addition, the experimenter will be pointing out important landmarks to help you learn the route as quickly and thoroughly as possible. Once you have memorized the route, you will then watch a videotape of the car travelling along the route so you can become familiar with the actual roadway scene. Once this is completed, the experimenter will ask you to recite the route from memory, to assure you know it thoroughly.

Driving Session:

During this session, you will be watching a videotape similar to that observed in the route memorization session, but now you must perform three concurrent tasks:

1. Watch for incorrect or missed turns. The automobile may make a number of navigational errors (incorrect or missed turns). You must now indicate to the experimenter when a navigation error has been committed. If a navigational error is committed, the automobile will perform an immediate maneuver to get back on the desired route. Once the automobile is back on track, indicate this to the experimenter, as well.

2. Another concurrent task involves watching for potential hazards in the roadway. In this case, the hazard will be a ball that appears in front of the automobile. In real driving situations, a ball rolling into the roadway is a warning sign that a child may be following close behind. You would normally apply the brake and approach with caution. In this study, applying the brake is achieved by pressing the left mouse button. You will be holding the mouse throughout the driving session so that you may hit the "brake" as quickly as possible. Once you press the mouse button, the potential hazard will disappear and you will proceed on as before. The ball will appear at random throughout the session.

3. The third concurrent task requires you to monitor the speed of the vehicle. Speed will be presented digitally. When the speed of the vehicle is 5 miles per hour over the posted speed limit, you are to report that to the experimenter by saying, "speeding."

It is important to note that all three tasks are important, and none should be sacrificed to enhance performance on the others. Consider these tasks in the context of driving a real automobile: You must be aware of your surroundings when navigating through an unfamiliar area to avoid getting lost; you should be aware of your speed to drive safely and avoid violations; and potential hazards in the roadway must be watched for at all times to avoid accidents.

Appendix D. Map and Directions used in the Route Memorization Session

DIRECTIONS

The car will initially be stopped, facing South.

Immediately make a left turn, and proceed east for 3 miles until you come to a stop sign.

Make a right turn and proceed south for 2 miles until you come to I-85.

Make a right turn onto I-85 and proceed west for 6 miles until you come to the Duke Street exit.

Proceed down the offramp and turn right onto Duke Street.

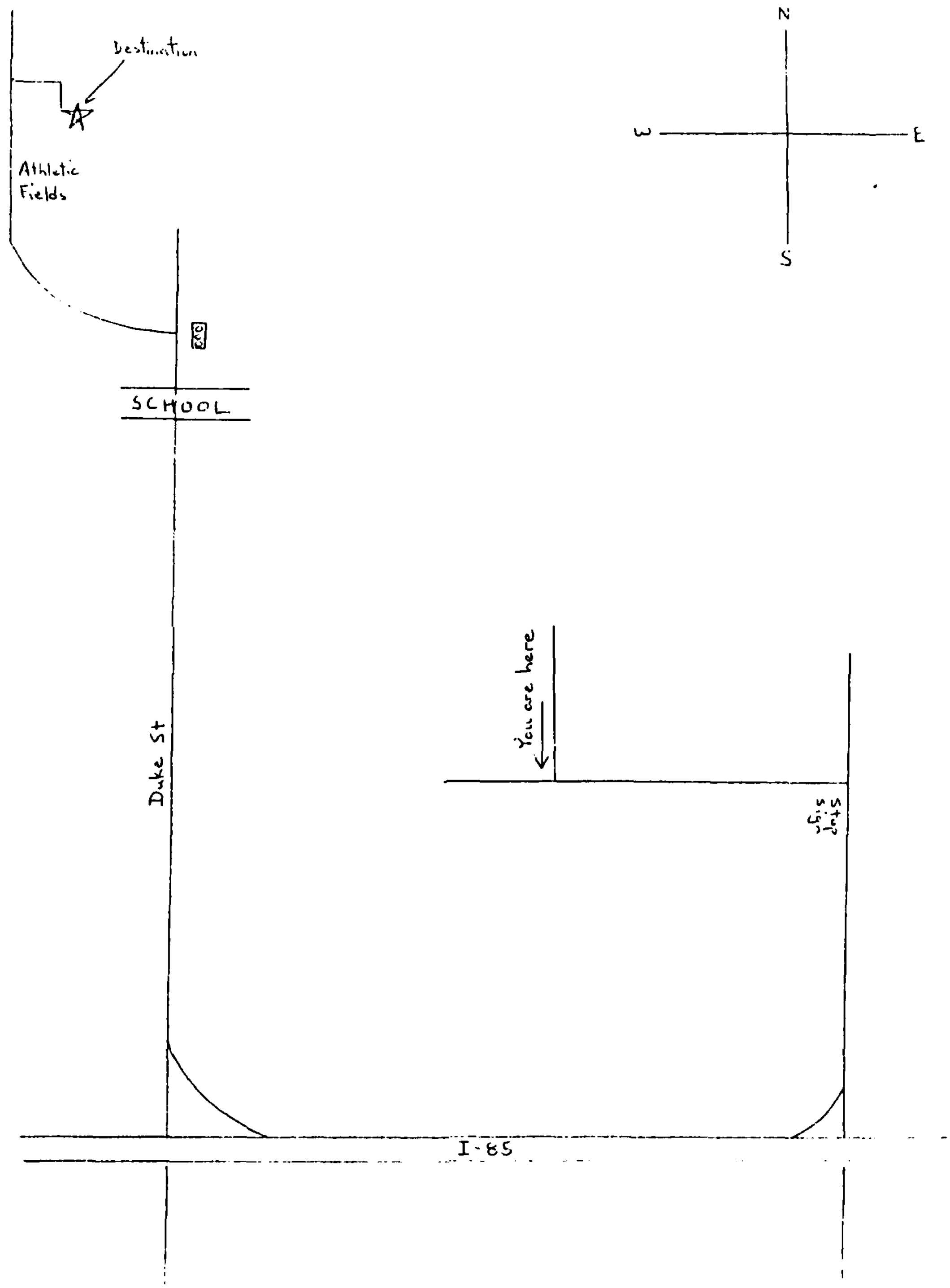
Proceed north for 5 miles. Once it appears you are leaving the business section of town, look for a school crossing sign and the word "school" written across the road.

Make a left turn at the stop light immediately following the school crossing signs.

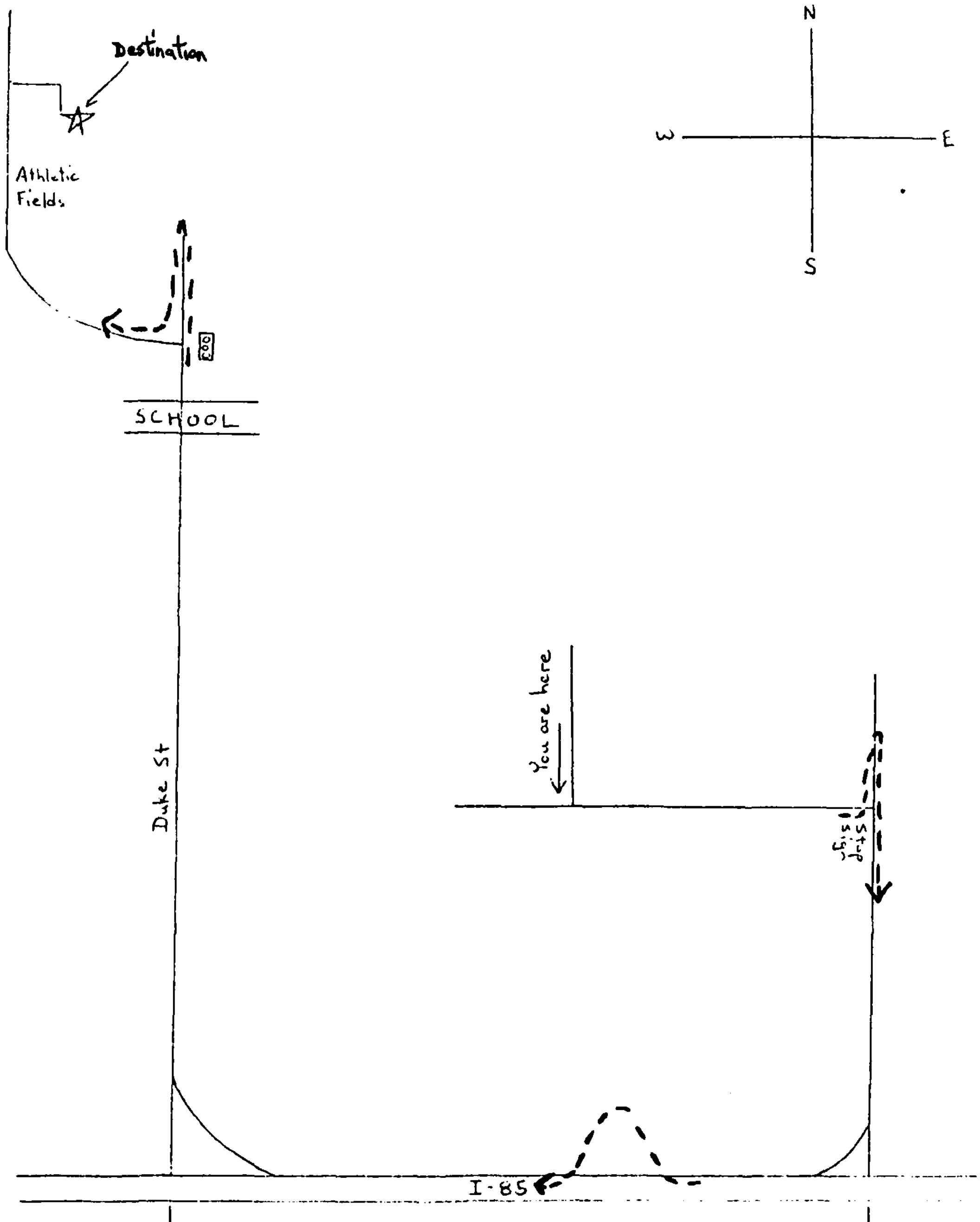
Proceed down this road for 1 mile. Look for a large empty parking lot and an athletic field (baseball backstop, football field) on the right side.

Make a right turn immediately after the athletic fields and proceed for 20 yards.

Make your first right into the school parking lot and stop.



Map Shown to Subjects



Map Indicating Navigation Errors
(dashed arrows)

Appendix E. Subject Questionnaire

SUBJECT NO. ____

AUTOMOTIVE STUDY QUESTIONNAIRE

We ask that you answer the following questions as thoroughly and as honestly as you can. If you feel that you cannot answer a question for any reason, simply leave it blank.

I. General Information

1. __________Gender
2. __________Age
3. __________How many years have you been driving?
4. Estimate the number of miles you drive each year:

___ 0-2,000 miles ___ 10,000-14,000 miles
___ 2,000-6,000 miles ___ 14,000-20,000 miles
___ 6,000-10,000 miles ___ 20,000 or more miles
(please check the appropriate box)

II. Experiment Information

1. How closely did the driving session approximate the actual driving of an automobile?

0 1 2 3 4 5
Not at all Somewhat Very Closely

2. Of the three tasks, on which did you concentrate most of your attention?

___ Navigation
___ Speed Monitoring
___ Potential Hazard Detection
___ All Three Equally As Much

3. Was it challenging to perform all three tasks at the same time?

___ Yes ___ No Please explain:

____
____
____

4. Were you able to perform the three tasks as well in this study as you do in a real automobile?

___ Yes ___ No Please explain:

____

____

5. Which task do feel you did the best at?

___ Navigation
___ Speed Monitoring
___ Potential Hazard Detection
___ All Three Equally As Well

6. Please write any comments you may have about the tasks:

____

____

____

III. Head-Up Display Information

1. Did the displaying of the speedometer numbers on the outside scene help or hinder your performance on the navigation task?

-5	0	5
Hindered Greatly	No Effect	Helped Greatly

2. Did the displaying of the speedometer numbers on the outside scene help or hinder your performance on the potential hazards detection task?

-5	0	5
Hindered Greatly	No Effect	Helped Greatly

3. For the speed monitoring task, would you prefer the numbers displayed on the outside scene, or positioned below the scene, as in a normal dashboard?

___ On scene ___ Normal Dashboard

Why? ______________________________

____

4. With regard to the speedometer numbers, what would you change that would make them easier to use?

___ Color
___ Size
___ Location

Please elaborate: ______________________________

____

5. How did you like having the numbers displayed on the outside scene?

-5	0	5
Disliked Much	Indifferent	Liked Much

Why? ______________________________

____

6. Irrespective of cost, would you ever consider owning a real automobile that displays important dashboard information on the outside environment?

   ___ Yes   ___ No

7. Any additional comments?

   ____

   ____

   ____